

SEA ICE SOLIDIFICATION: THE PHYSICAL ORIGIN OF MACROSCOPIC PROPERTIES

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LONG TERM GOALS

The long term goals of this project are to construct a quantitative understanding of the physical mechanisms responsible for the creation and evolution of the volumetric phase fraction of sea ice. In parallel with the development of solidification research, we aim to advance the coupling and interaction with electromagnetic signature modeling. It should be stressed that the approach is entirely general so that the results are broadly applicable and useful in understanding the phase evolution of any binary alloy undergoing unidirectional solidification. Therefore, although we emphasize the saltwater system, the implications for the mechanical and thermophysical properties span fields from metallurgy to geophysics.

OBJECTIVES

Sea ice is observed to be a mixture of pure ice and bulk solution or salts in precipitate. Microstructure on the scale of fractions of millimeters is controlled by molecular diffusion of heat and mass (Wettlaufer, 1992), and larger scale structures are controlled by buoyancy driven convection and the concomitant phase changes adjacent to and within the ice sheet (Wettlaufer, 1997). The main issue surrounding our research is that the two phase structure of sea ice influences important geophysical phenomenon, *and* our ability to detect them. The geophysical importance of the liquid fraction and the associated redistribution of impurities, is that they control the (1) anomalous thermal, (2) mechanical, (3) electromagnetic, and (4) acoustic properties. Air/sea/ice heat transfer is mediated by the volume fraction of seawater in sea ice, i.e., the liquid fraction, because it determines the bulk thermal diffusivity of the material. This is of particular importance for thin ice, formed in leads, which dominate the wintertime surface heat budget. The mechanical properties of sea ice are similarly controlled by the liquid fraction, creating bulk moduli that depend on its spatial distribution, and therefore on the growth history. The liquid fraction and microstructure control electromagnetic response of sea ice; optical wavelengths influence the productivity of ice biota, and radio and microwavelengths are crucial for the detection of different ice types. The electromagnetic and acoustic responses are wavelength dependent, so microstructural properties control our ability to monitor ice properties and behavior remotely. We are searching for the underlying causes for, and evolution of, the liquid fraction. At the initiation of our research program, there existed *no* first principles theory for the evolution of the liquid fraction of sea ice, and hence no rigorous method for testing electromagnetic and acoustic signature models. Our main objectives during this phase of the work were to cast a predictive theory for the liquid fraction of growing sea ice into the framework

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of the theory of mushy layers and to refine surface and volume scattering electromagnetic signature model for thin sea ice for which the theory of mushy layers is appropriate.

APPROACH

Solidification: We have used fundamental mixture theory, laboratory experimentation and have begun analyzing field data all centered around rapid solidification of the ocean initiated by the ONR sponsored Lead Experiment (The LeadEx Group, 1993). Over thirty laboratory experiments were performed at the Institute of Theoretical Geophysics, within the Dept. of Applied Mathematics & Theoretical Physics, University of Cambridge, in collaboration with Professor H.E. Huppert and Dr. M.G. Worster. Motivated by the data, we have developed a theoretical understanding of phase fraction dynamics, that required treating the interaction between solidification and fluid mechanics.

Scattering Theory: The electromagnetic signature component is primarily theoretical, much of which is at the forefront of modern inverse theory. The work draws upon airborne synthetic aperture radar and surface based observations. The theory has been aided substantially by previously funded ONR research to develop a model that treats scattering from surface roughness which overlies a region having a vertical profile of dielectric properties. A model was developed to treat sea ice in the relevant lower range of microwave frequencies (Winebrenner et al., 1995).

ACCOMPLISHMENTS

We have completed the mean field mixture theory relevant to the solidification from above of a sub-eutectic binary alloy. We have completed the analysis of the experiments discussed above involving saltwater and have applied the general theory to find two modes of instability (described below) are relevant to the system. We have written software necessary to allow the analysis to be applied to field data from LeadEx. We have applied the theory in order to calculate the space-time profile of phase fraction. We have begun using this data as input to the scattering theory. We have developed new theory to identify the phase fraction instabilities in ours and other systems as well as in the field data.

SCIENTIFIC/TECHNICAL RESULTS

We have identified the basic mechanisms responsible for the initial formation of brine channels (Wettlaufer et al., 1997 a, b, and Worster and Wettlaufer, 1997), which exert a strong influence on horizontal signature variations. Their existence and long time evolution has been studied for many years, but the mechanisms associated with their formation had not been rigorously described or quantified. We found that when the ice reaches a critical thickness, intercrystalline brine is released, and concomitant compositional convection redistributes brine by accommodating flow between the underlying water, and the intercrystalline spaces. Upward flow induces freezing, and downward flow induces melting; the competition focuses melting into localized regions larger than the intercrystalline spacing, and this ultimately forms the brine channels that we have observed. These mechanisms are distinguished by two modes of instability (Worster and Wettlaufer, 1997). These both involve the interaction of fluid mechanics and solidification. The mode of instability leading to channel formation is called the "mushy-layer mode" and involves a long range overturning within the sea ice. This is the first rigorous quantification of convection in sea ice and it is characterized by a porous media Rayleigh number.

We have constructed a theory for the sensitivity of crystallographic fabrics to salinity (Weeks and Wettlaufer, 1996). We have identified a new mechanism for the upward transport of brine in a polycrystal based on the ideas of *grain boundary melting* (Dash et al., 1995; Wettlaufer et al., 1997c). This is the only mechanism which possesses an unambiguous directionality in the transport of intercrystalline liquid from warm to cold regions. Hence, we believe it to be operative during the surface salination of young sea ice that drastically alters the electromagnetic signature.

Inverse theory (Sylvester et al., 1996) has led to a new method to directly estimate thickness for electromagnetically lossless problems. Extending these results to a more lossy model for sea ice will allow a direct coupling to solidification theory.

IMPACT FOR SCIENCE

Our results clearly show that saltwater is an important transparent analogue for metallurgical systems, and in other areas of materials research pursued in ONR's Department of Engineering, Materials, and Physical Science. The formation of zero solid fraction domains has deleterious effects on the properties of technological materials. Our study requires the coupling of microscopic and macroscopic phenomena, and a basic understanding of how these couplings control material properties constitutes a research priority that cuts across the boundaries of varied disciplines and hence address a broad range of the ONR's mission for the Navy. Our results have *commercial consequences* for the casting of ingots, the coarsening and annealing of ceramics and powders, and the nondestructive evaluation of polycrystalline alloys. The work advances the role that new materials and efficient materials processing play in the country's agenda for technological competitiveness. Hence, while our sea ice studies offer a basic challenge to the geophysical agenda at the forefront of ONR's High Latitude Program they act as a test bed for issues of relevance to a host of other materials and applications within the mandate of other ONR departments. Finally, our results make direct contact with the problem of understanding the growth of the Earth's inner core from the iron-alloy liquid core (Bergman and Fearn, 1994), the geodynamo (Lister and Buffett, 1995), solidifying magmas (Huppert, 1990) and industrial casting processes (Worster, 1997).

TRANSITIONS

We have now begun a systematic program to link the basic results described above to the field data in hand. In the near future Dr. K. Nagashima, who has recently done seminal research in the freezing of solutions, will begin work with us in Seattle contingent upon receiving support from the Japanese Society for the Promotion of Science.

RELATED PROJECTS

A related project entitled Interfacial Melting and Frost Heave in Ice is supported by the NSF. This project focuses on the microscopic contributions to the existence of interfacial liquid in ice at temperatures below the bulk freezing point and the dynamics of this liquid.

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